State of the art of electron spectrometers at the ALS

Alexei Fedorov [$$]

/November 13 2001, ALS monthly meeting/

$$ *Supported by:*

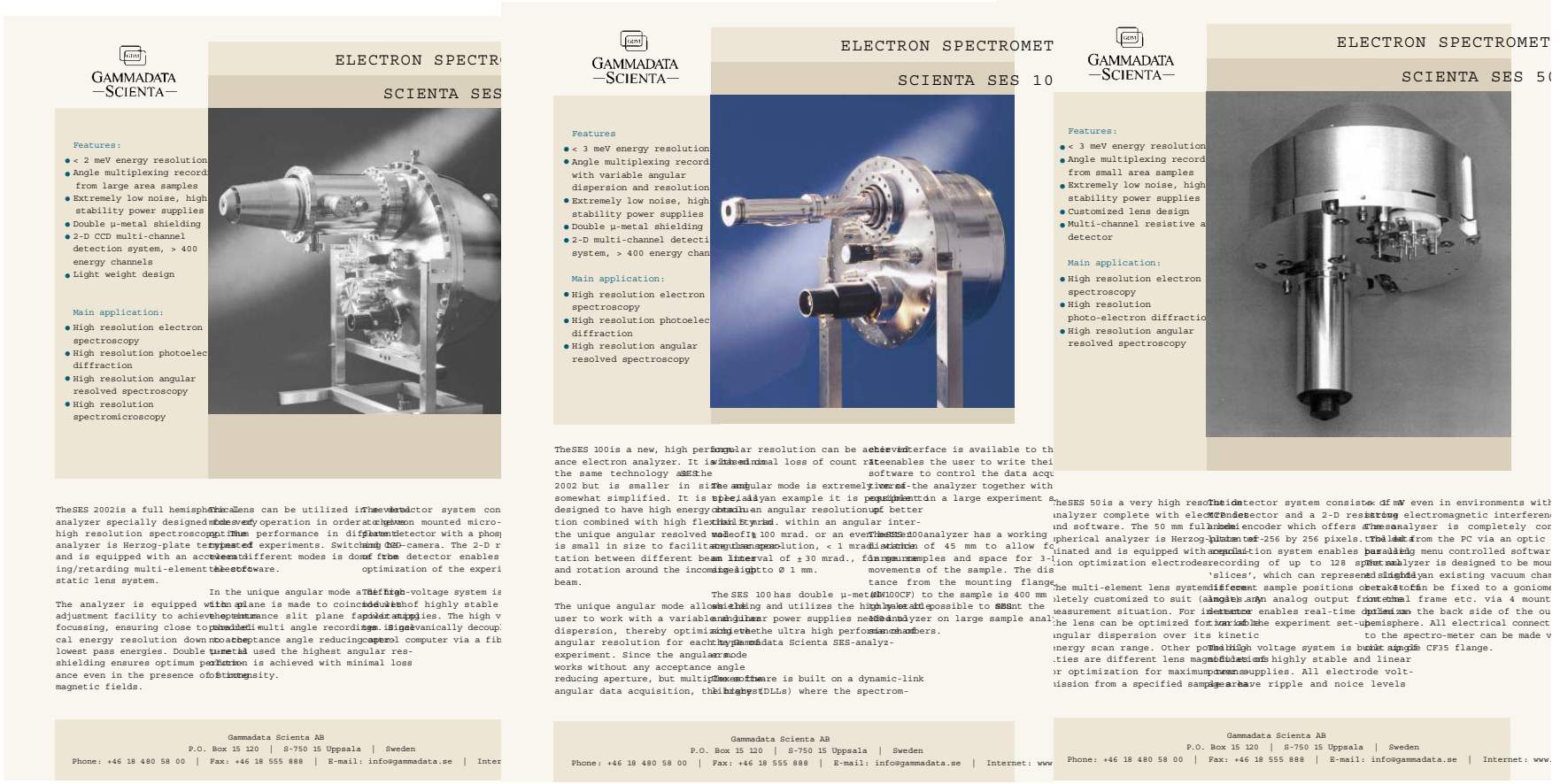
125 Years CU-BOULDER 1876 • 2001 *Minds to Match Our Mountains*

BERKELEY LAB

Plan:

Orientation
Photoelectron Spectroscopy
Instrumentation
Gammadata-Scienta spectrometers
Examples of the research

Scienta spectrometers at ALS



GAMMADATA —SCIENTA—

ELECTRON SPECTR

SCIENTA SES

Features:

- < 2 meV energy resolution
- Angle multiplexing record
  from large area samples
- Extremely low noise, high
  stability power supplies
- Double μ-metal shielding
- 2-D CCD multi-channel
  detection system, > 400
  energy channels
- Light weight design

Main application:

- High resolution electron
  spectroscopy
- High resolution photoelec
  diffraction
- High resolution angular
  resolved spectroscopy
- High resolution
  spectromicroscopy

TheSES 2002is a full hemispherical lens can be utilized in the ...ve detector system con
analyzer specially designed for very ... operation in order to achieve ...on mounted micro-
high resolution spectroscopy. The performance in different ... detector with a phos
analyzer is Herzog-plate ... types of experiments. Switching ... CCD-camera. The 2-D r
and is equipped with an accelera... modes of the detector enables
ing/retarding multi-element lens ... software. optimization of the experi
static lens system.

In the unique angular mode a ... high-voltage system is
The analyzer is equipped with ... plane is made to coincide with ... of highly stable
adjustment facility to achieve ... instrument slit plane for all ... supplies. The high v
focussing, ensuring close to ... limited multi angle recordings is ... galvanically decoup
cal energy resolution down to ... acceptance angle reducing ... computer via a fib
lowest pass energies. Double ... is used the highest angular res-
shielding ensures optimum ... olution is achieved with minimal loss
ance even in the presence of ... intensity.
magnetic fields.

Gammadata Scienta AB
P.O. Box 15 120 | S-750 15 Uppsala | Sweden
Phone: +46 18 480 58 00 | Fax: +46 18 555 888 | E-mail: info@gammadata.se | Inter

GAMMADATA —SCIENTA—

ELECTRON SPECTROMET

SCIENTA SES 10

Features

- < 3 meV energy resolution
- Angle multiplexing record
  with variable angular
  dispersion and resolution
- Extremely low noise, high
  stability power supplies
- Double μ-metal shielding
- 2-D multi-channel detecti
  system, > 400 energy chan

Main application:

- High resolution electron
  spectroscopy
- High resolution photoelec
  diffraction
- High resolution angular
  resolved spectroscopy

TheSES 100is a new, high perfo... angular resolution can be achieved ...interface is available to th
ance electron analyzer. It is ... minimal loss of count ra... It enables the user to write thei
the same technology as ... The ... software to control the data acqu
2002 but is smaller in size and ... angular mode is extremely ... of the analyzer together with
somewhat simplified. It is ... example it is possible to ... in a large experiment a
designed to have high energy ... obtain an angular resolution ... of better
tion combined with high flexibil... than 1°. and. within an angular inter-
the unique angular resolved mo... of ± 100 mrad. or an even ... The SES 100 analyzer has a working
is small in size to facilitate ... angular range, ... resolution, < 1 mrad. ... distance of 45 mm to allow fo
tation between different beam ... intervall of ± 30 mrad., for ... manipulation samples and space for 3-
and rotation around the incoming ... light to Ø 1 mm. ... movements of the sample. The dis
beam. tance from the mounting flange

The SES 100 has double μ-metal ... (CF100CF) to the sample is 400 mm
shielding and utilizes the high ... which makes it possible to ... mount the
The unique angular mode allows ... and linear power supplies need ... analyzer on large sample anal-
user to work with a variable ... angular ysis chambers.
dispersion, thereby optimizing ... between the ultra high performance ...
angular resolution for each type ... of Gammadata Scienta SES-analyz-
experiment. Since the angular ... mode
works without any acceptance ... angle
reducing aperture, but multiple ... The software is built on a dynamic-link
angular data acquisition, this ... libraries (DLLs) where the spectrom-

Gammadata Scienta AB
P.O. Box 15 120 | S-750 15 Uppsala | Sweden
Phone: +46 18 480 58 00 | Fax: +46 18 555 888 | E-mail: info@gammadata.se | Internet: www

GAMMADATA —SCIENTA—

ELECTRON SPECTROMET

SCIENTA SES 5

Features:

- < 3 meV energy resolution
- Angle multiplexing record
  from small area samples
- Extremely low noise, high
  stability power supplies
- Customized lens design
- Multi-channel resistive a
  detector

Main application:

- High resolution electron
  spectroscopy
- High resolution
  photo-electron diffractio
- High resolution angular
  resolved spectroscopy

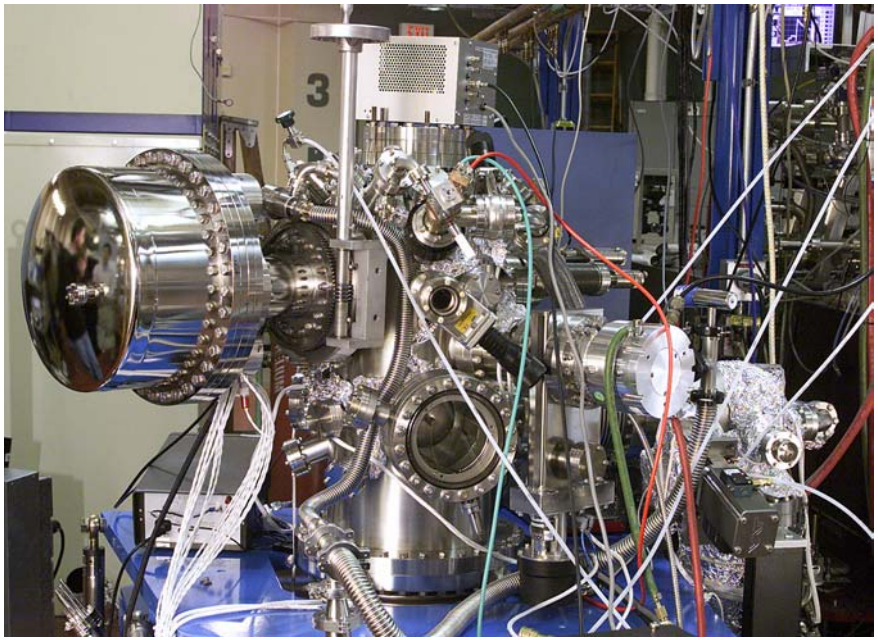
TheSES 50is a very high reso... The detector system consists ... of mV even in environments with
analyzer complete with elect... and detector and a 2-D resistive ... electromagnetic interferen
and software. The 50 mm full ... hemel encoder which offers ... These analyser is completely co
spherical analyzer is Herzog-plate ... mentor-256 by 256 pixels. The ... ter from the PC via an optic
minated and is equipped with an ... acquisition system enables ... parallel menu controlled softwar
tion optimization electrodes ... recording of up to 128 spectra ... analyzer is designed to be mou
'slices', which can represent ... a high ... an existing vacuum cha
The multi-element lens system ... different sample positions or ... tact to ... can be fixed to a goniome
pletely customized to suit (angle ... an analog output from ... mal frame etc. via 4 mount
measurement situation. For ... detector enables real-time ... lens on the back side of the ou
The lens can be optimized for ... angular ... of the
angular dispersion over its kinetic ... to the spectro-meter can be made v
energy scan range. Other ... The high voltage system is built ... single CF35 flange.
ties are different lens ... highly stable and linear
or optimization for maximum ... power supplies. All electrode volt-
mission from a specified sample ... have ripple and noice levels

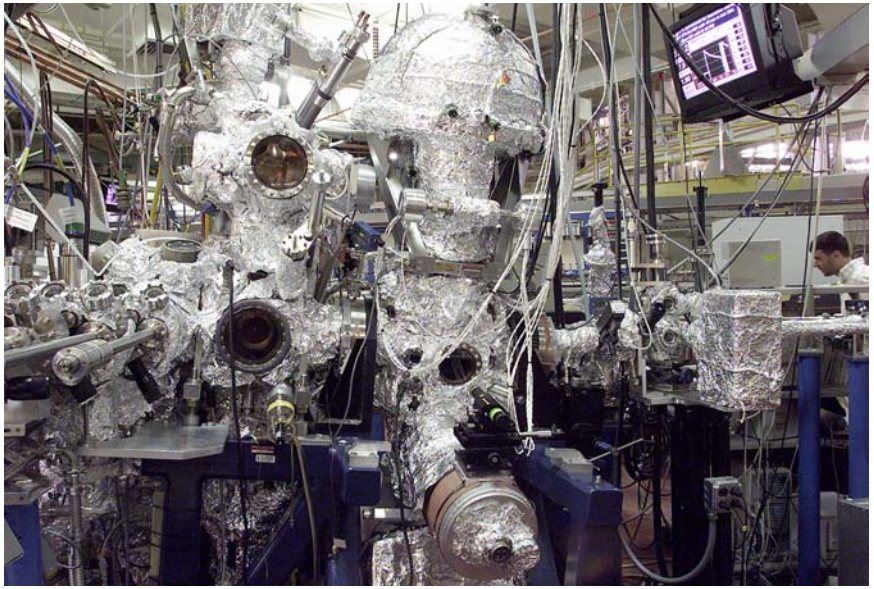
Gammadata Scienta AB
P.O. Box 15 120 | S-750 15 Uppsala | Sweden
Phone: +46 18 480 58 00 | Fax: +46 18 555 888 | E-mail: info@gammadata.se | Internet: www.

BL-10.0.1 (2)
BL-12.0.1 (1)

BL-7.0.1
BL-12.0.1
BL-9.3.2
BL-8.0.1

NONE


3



Other facilities also have it:

NSLS, Brookhaven: SES-200 (1)

SSRL, Stanford: SES-200 (1+)

SRC, Stoughton: SES-200 (1+), SES-50

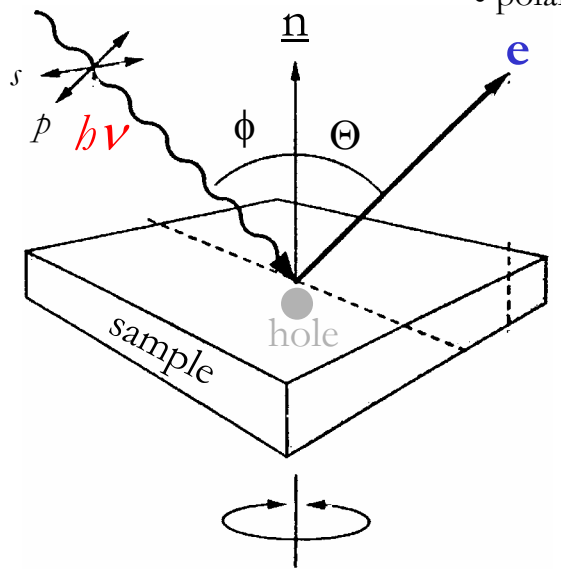
CAMD, Baton Rouge: SES-200 (1)

Photoemission /inverse photoemission/

Experiment

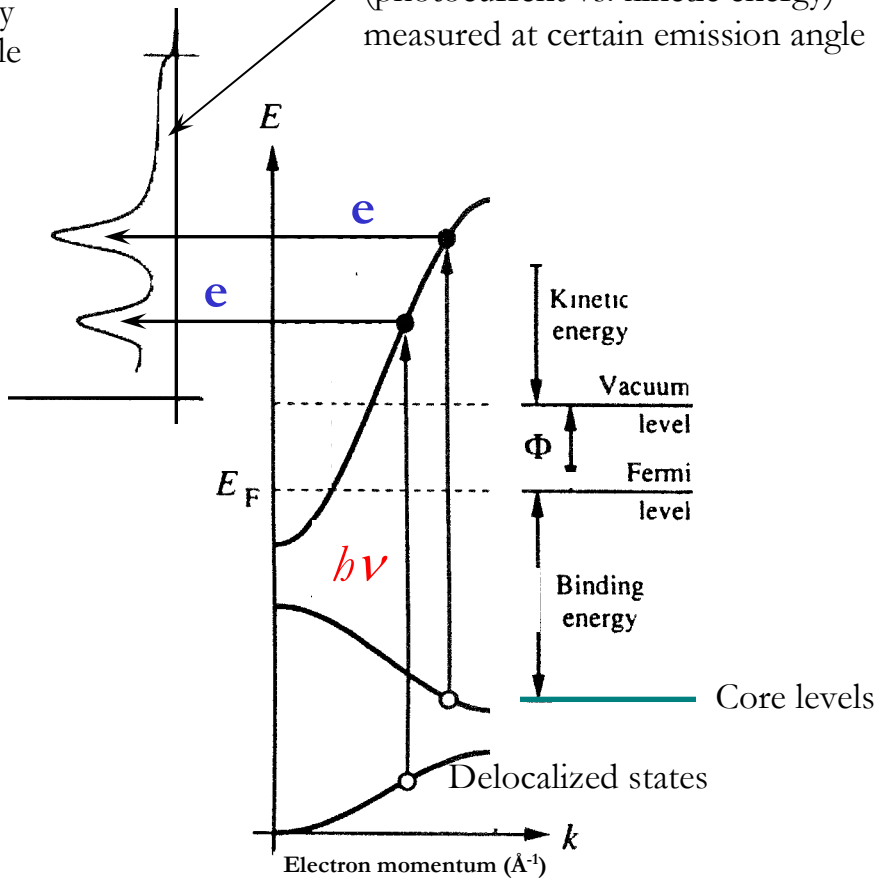
Excitation Radiation
- photon energy
- polarization
- angle of incidence

Photoelectrons
- kinetic energy
- emission angle
- polarization



Data

Energy Distribution Curves
(photocurrent vs. kinetic energy)
measured at certain emission angle



Important parameters:

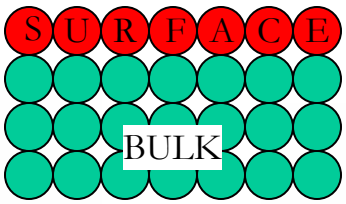
Energy resolution (~20 meV)

Angular resolution (~2°)

Aim: learn Electronic structure or Chemical composition

Approach: fitting Data using appropriate models

Surface core level shifts in 4-f metals



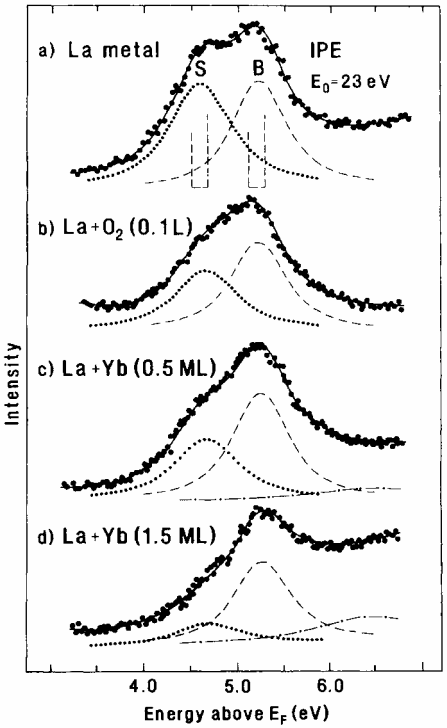


FIG. 2. Inverse photoemission spectra in the region of the $4f^1$ electron-addition state, taken at a primary electron energy of E_0=23 eV: (a) a clean surface of La metal; (b) after exposure to 0.1 L of oxygen; after coverage by (c) 0.5 monolayer (ML) of Yb and (d) 1.5 ML of Yb. The solid curves through the data points are the results of least-squares fits; for details see text.

A.V. Fedorov et al., PRL 70, 1719 (1992)

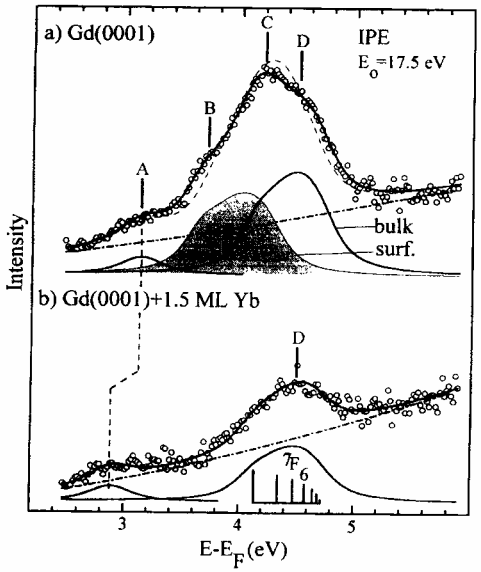


FIG. 1. IPE spectra of Gd(0001) in the region of the $4f^8$ electron-addition state, taken at a primary electron energy of E_0 = 17.5 eV: (a) clean Gd(0001) surface; (b) after coverage by 1.5 ML of Yb metal. Spectral features *B*, *C*, and *D* of clean Gd(0001) originate from $4f^8$ electron-addition states in the topmost surface layer (shaded) and in the bulk (solid curve); the vertical-bar diagram in (b) gives the energies and relative intensities of the individual ^7F_J bulk multiplet components. The solid curves through the data points in (a) and (b) represent the results of the best least-squares fits. The dashed curve in (a) was obtained in a fit where $\delta_s^{ea} = \delta_s^{er}$ was assumed. For details see text.

A.V. Fedorov et al., PRL 73, 601 (1994)

Electronic structure of High Temperature Superconductor And Ferromagnetic Gd

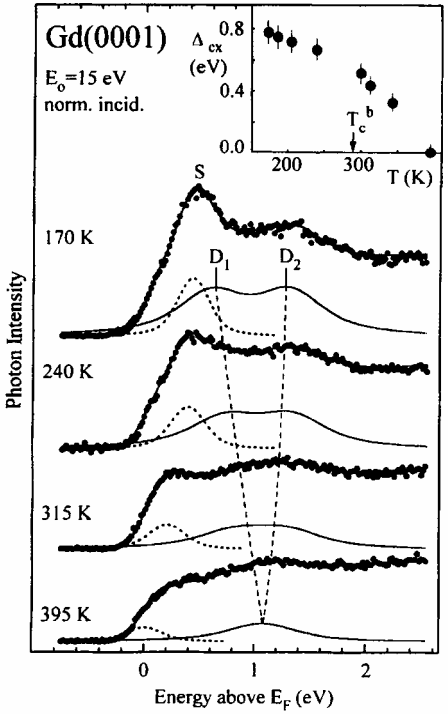


FIG. 4. Least-squares-fit analysis of selected inverse-photoemission spectra of Gd(0001) from Fig. 1 (for details, see text). The inset gives the exchange splitting Δ_{ex} as a function of temperature.

A.V. Fedorov et al., PRB 50, 2739 (1994)

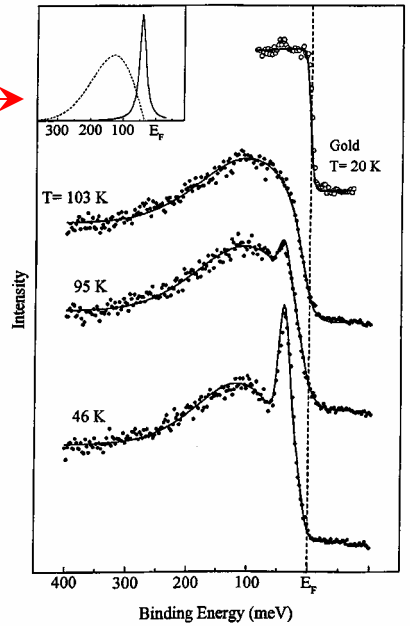


FIG. 2. Sample spectra at different temperatures showing the fit obtained using the two functions and background described in the text. The inset shows the two functions used in the fitting procedure. The parameter Δ_0 used in the latter fitting represents the separation of the leading edge of the broad peak from E_F, the Fermi level. The upper spectrum represents the Fermi edge obtained from an evaporated gold film.

VOLUME 82, NUMBER 10 PHYSICAL RE

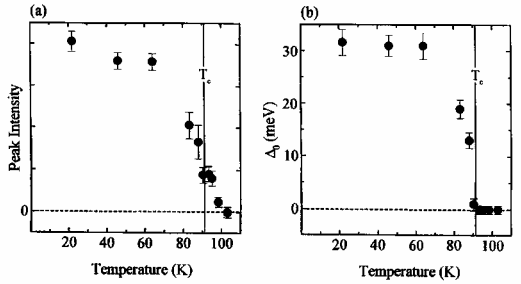
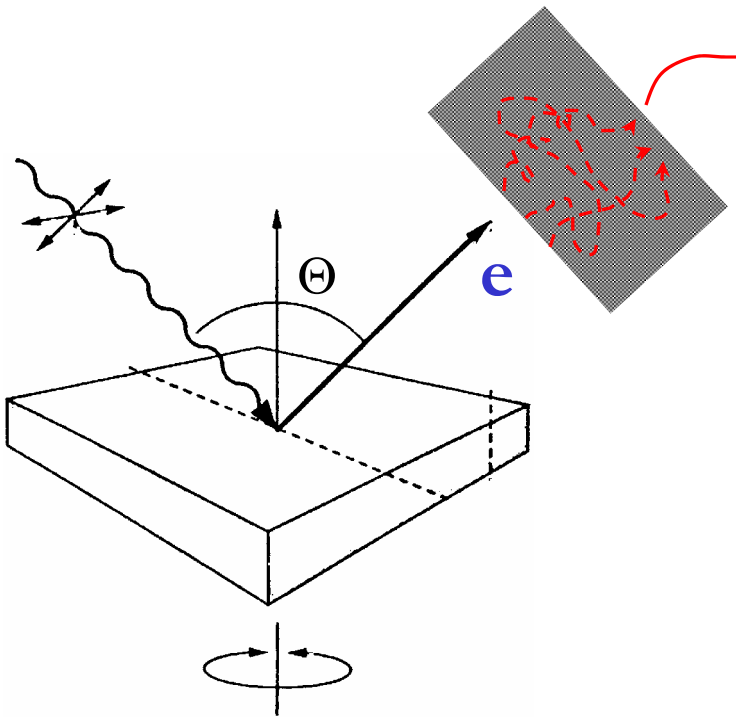


FIG. 3. (a) Intensity of the sharp peak as a function of the sample temperature. The transition temperature T_c is indicated. (b) The gap, Δ_0, between the leading edge of the broad peak and the Fermi level as obtained from the fitting procedure.

A.V. Fedorov et al., PRL 82, 2179 (1999)

What is an electron spectrometer?



Intensity, Energy, and Emission angle

Plus:

Excellent resolution
Multiplexing

Good apparatus

Hyperbolic field analyzer

/*M. Jacka et al., RSI 70, 2282 (1999)*/

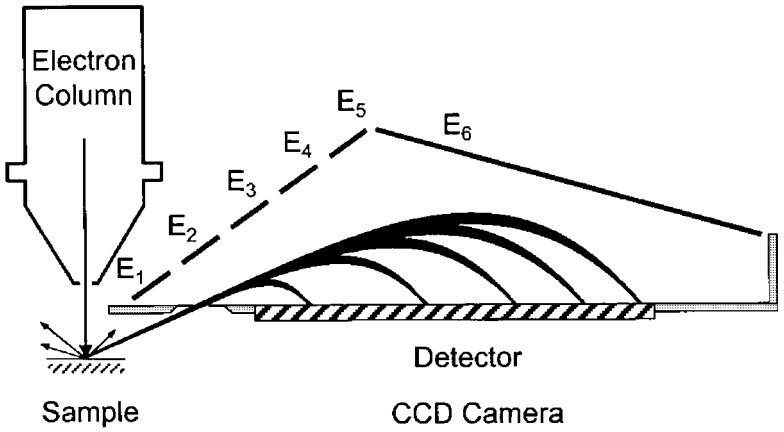


FIG. 5. The prototype HFA and electron gun, showing some electron trajectories with differing energy. The field is constructed by applying the appropriate voltages to electrodes E_1–E_6.

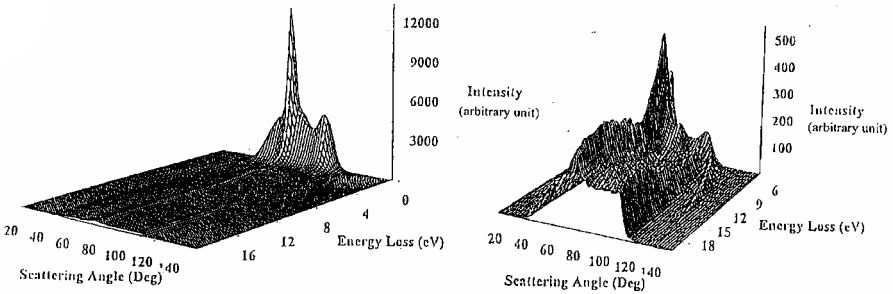


FIG. 10. 3D view of energy loss spectrum in e+HOPG collisions at electron incident energy of 50 eV, the left figure shows the whole spectrum and only inelastic features are shown in the right one.

Display Analyzer
/single energy, all angles/

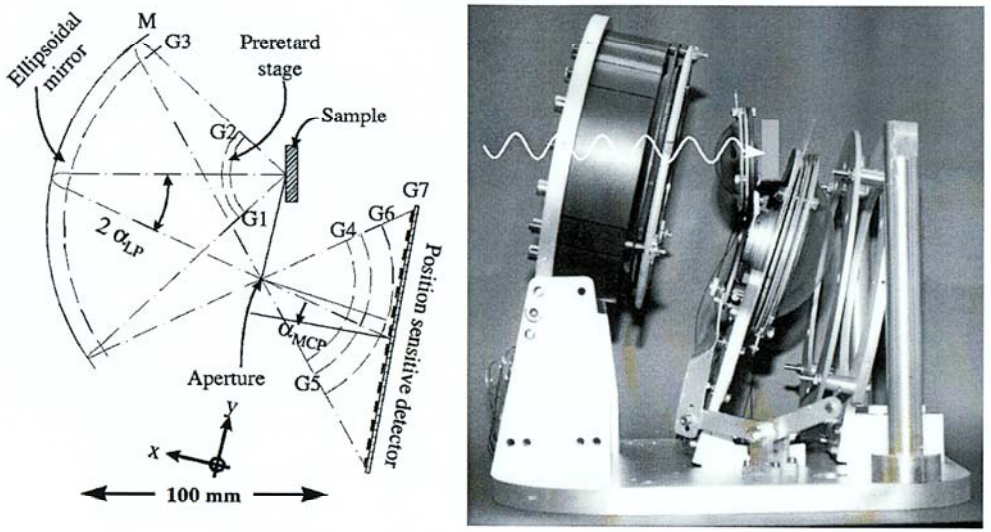


FIG. 1. Sketch showing the operation principal of the ellipsoidal display analyzer (left) with its main components, the preretardation stage, the ellipsoidal low-pass mirror, the aperture, the high-pass filter, and the detector. A photograph of the analyzer (side view) with the shielding removed is shown on the right. The light (wavy line) enters the analyzer in the horizontal plane (56° relative to the sample normal).

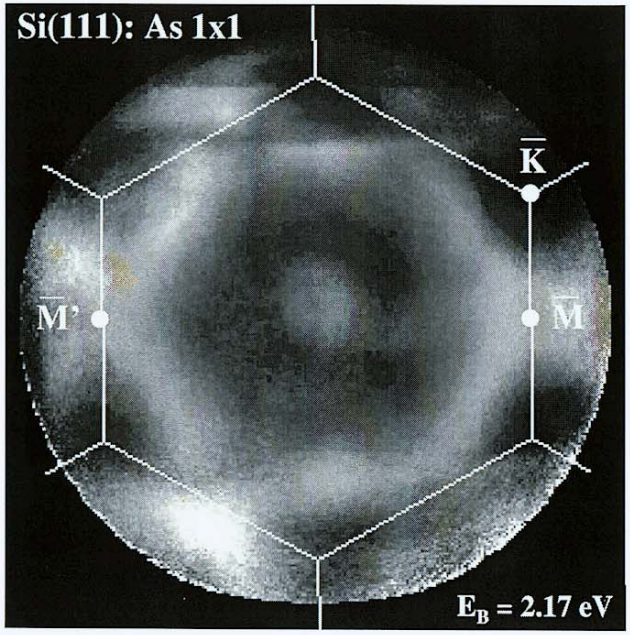


FIG. 7. Photoelectron intensity vs parallel wave vector $I(\mathbf{k}_\parallel)$ at $E_B = 2.17$ eV binding energy for the arsenic-terminated Si(111) surface. The surface Brillouin zone with the high-symmetry points is shown by a white line. At this binding energy the emission is dominated by the lone-pair arsenic surface state showing almost hexagonal symmetry. Total acquisition time is 100 s.

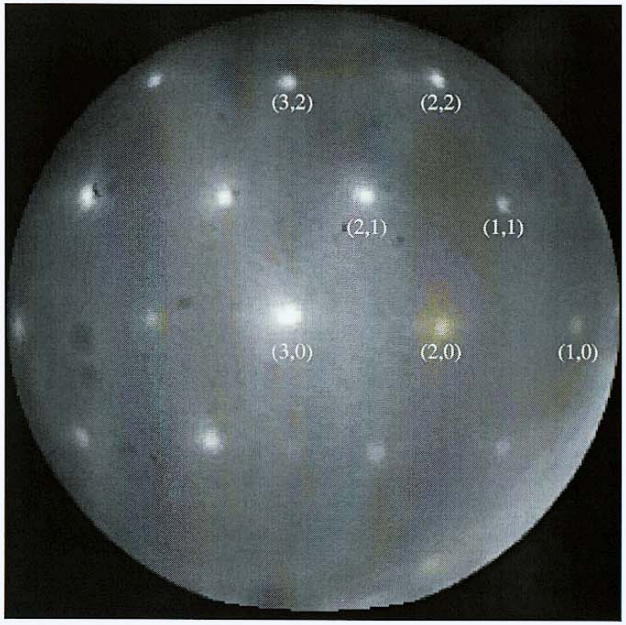


FIG. 8. LEED image of Si(111):As 1×1 taken with the ellipsoidal display analyzer at a kinetic electron energy of $E = 470$ eV and with an aperture of $r_A = 0.5$ mm. LEED images can be taken without moving the analyzer or sample. The LEED pattern is tilted relative to conventional LEEDs because of the 56° incidence angle of the primary electron beam. Some reflections of the 1×1 hexagonal surface Brillouin zone are indexed for clarity.

Double toroidal analyzer

/ *C.Miron et al., RSI 68, 3728 (1997)* /

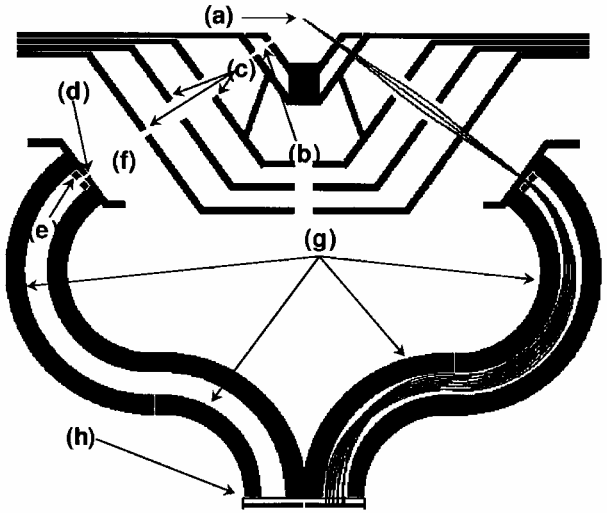


FIG. 3. Numerical simulation of electron trajectories with the DTA. The DTA main parts: (a) interaction region; (b) the two elements collimator; (c) focusing elements of the conical lens; (d) DTA input slit; (e) correction rings; (f) field-free region; (g) the four "toroidal" deflection plates; and (h) focusing region.

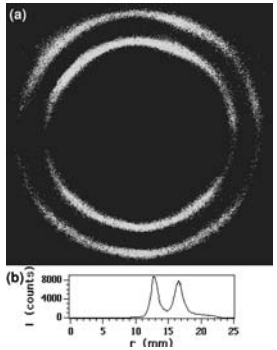


FIG. 8. a) The image on the PSD of the $1s(N_2,N_2)$ photoelectrons of N_2O molecule excited with $h\nu$=470 eV photons, recorded with the DTA. b) The corresponding $I(r)$ spectrum.

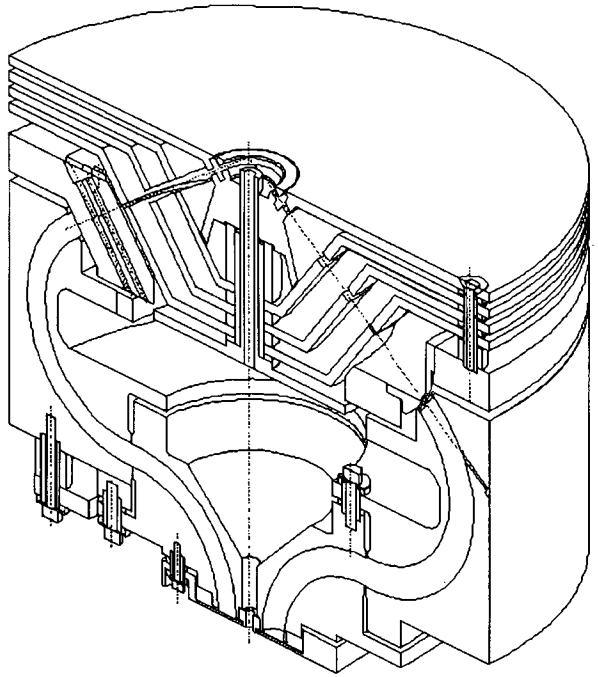


FIG. 5. Three dimensional view of the DTA's mechanical setup.

Energy window: $\Delta E \sim 15\%$ PE

Resolving power: $E_p/\delta E \sim 100$

Suggested reading:

- ✓ B. Wannberg, U. Gelius, and K. Sieghban, J. Phys. E, Sci. Instrum. 7, 149 (1974)
- ✓ R.C.G. Leckey, J. Electron Spectr. Relat. Phenom. 43, 183 (1987)

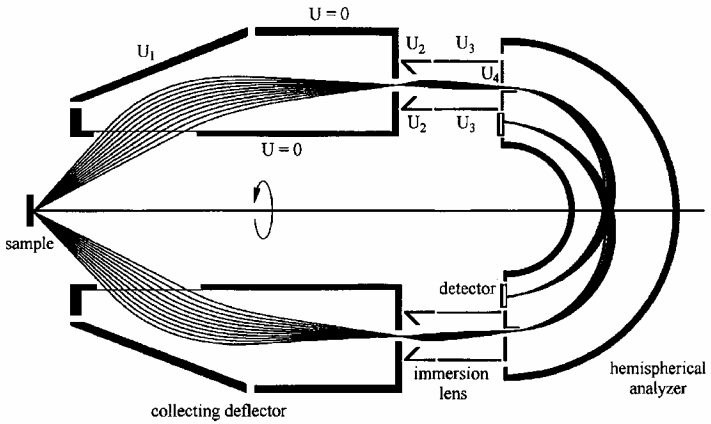
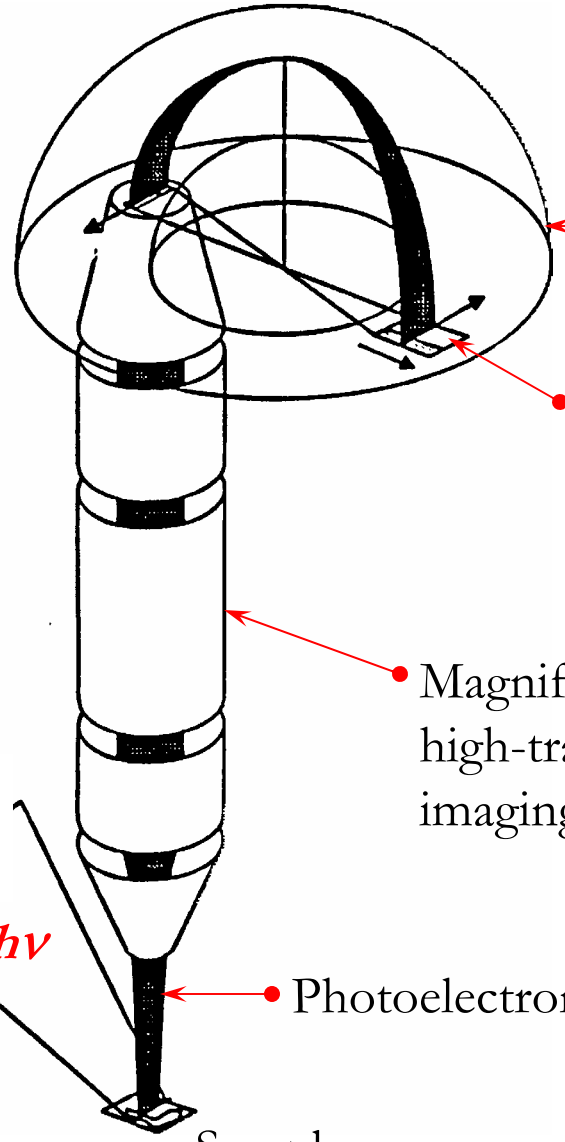


FIG. 2. A configuration of a high-transmission energy analyzer that consists of a collecting mirror of Fig. 1, a hollow coaxial cylindrical lens, and a hemispherical deflector.

V.D. Belov and M.I. Yavor, RSI 71, 1651 (2000)

New Instrumentation from Gammadata-Scienta

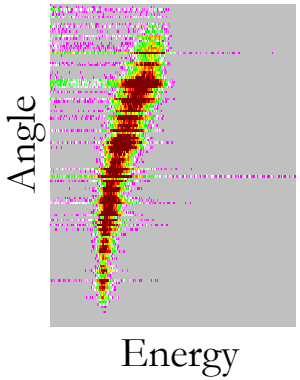


Wide-band Energy Analyzer

2-Dimensional (Energy and Angle) high-resolution electron detector

$E_p/\delta E$ ~1400
E_p= 2eV, <2meV
$\delta\Theta$~10 mrad
δS~9 μm

Magnifying high-transmission imaging Electron Lens



Excitation radiation

hν

Photoelectrons

Sample

2-dimensional detector
/Micro-channel plates coupled to the phosphor screen/

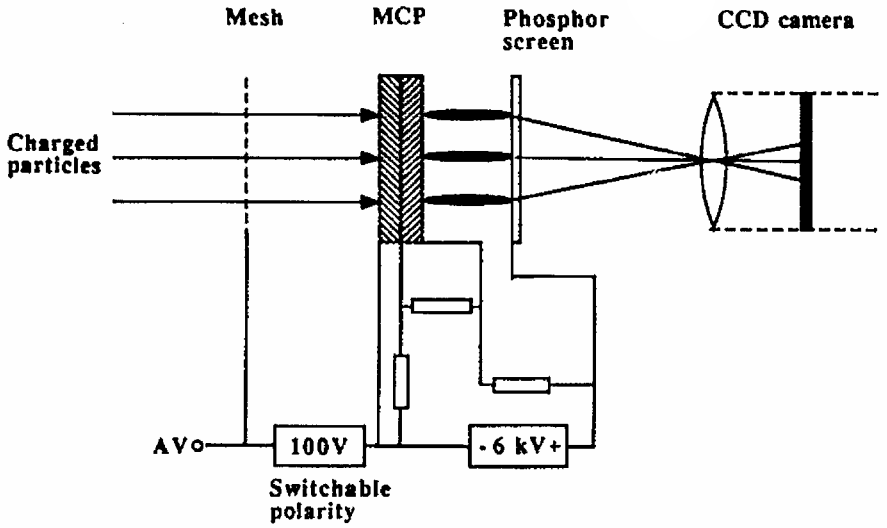
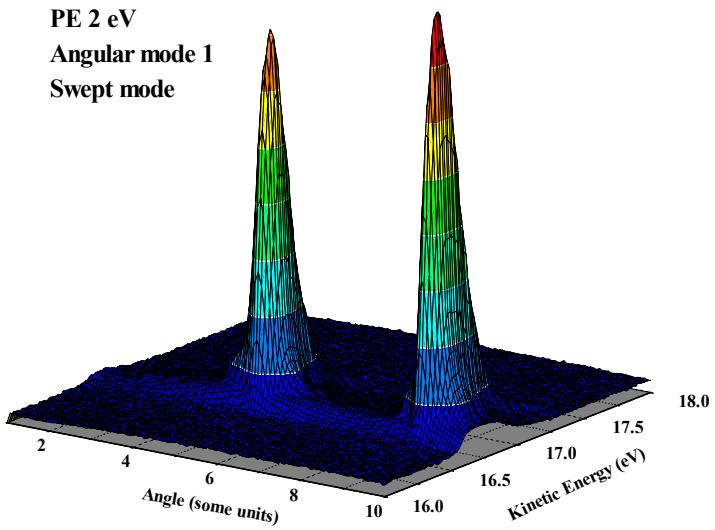
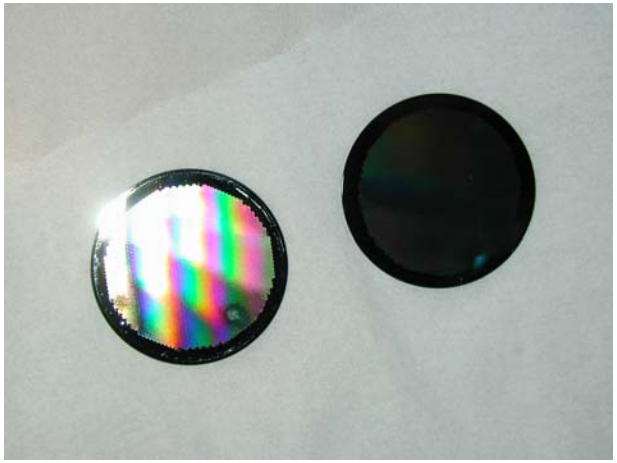


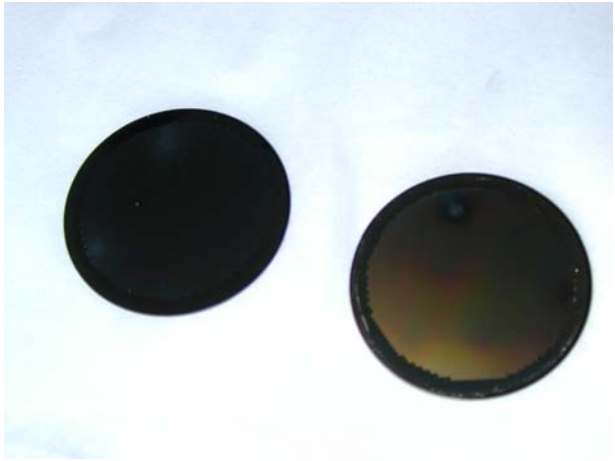
FIG. 12. Schematic drawing of the detection system.

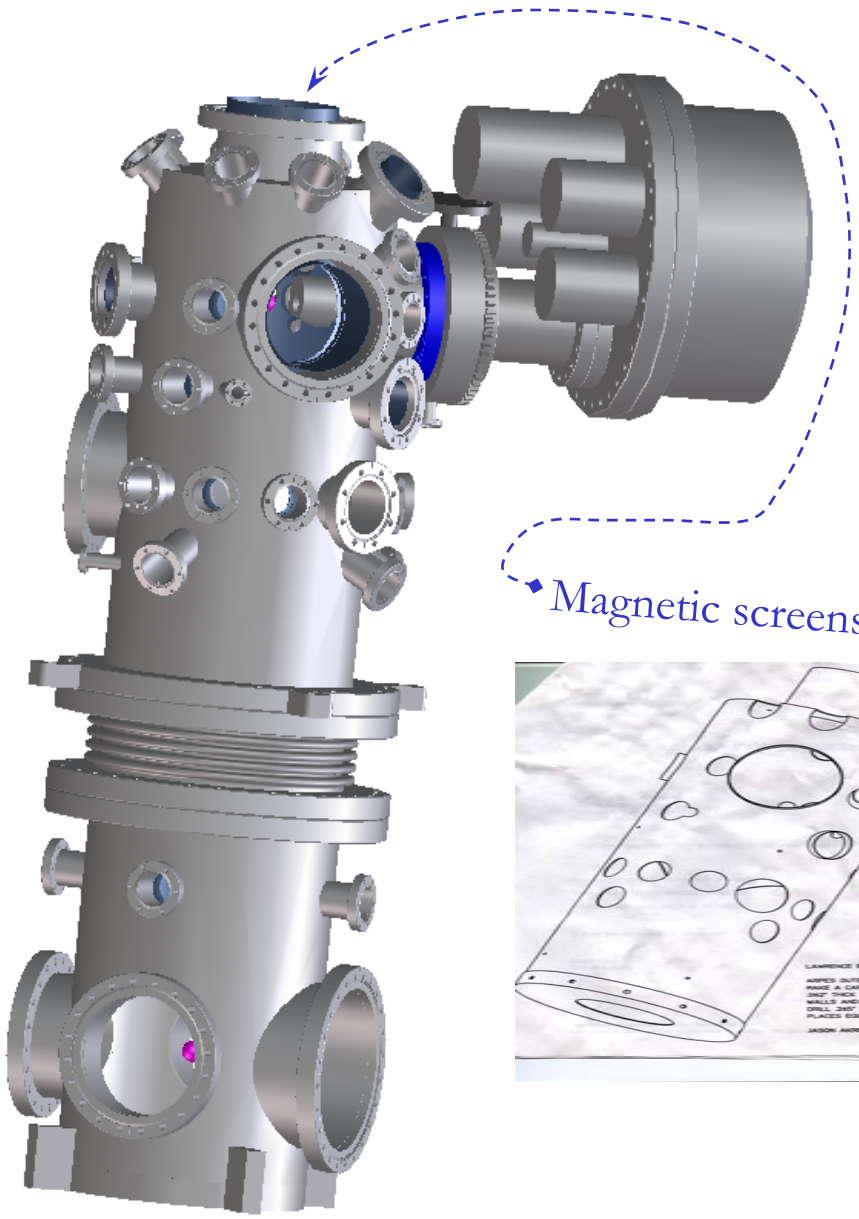
Is it: { Fast, Uniform, Linear, Stable } ?

Solving detector mysteries



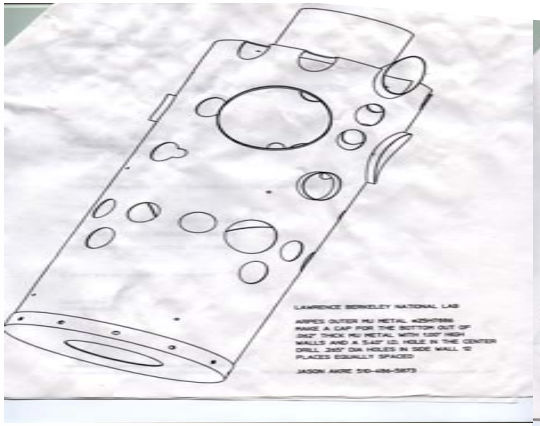


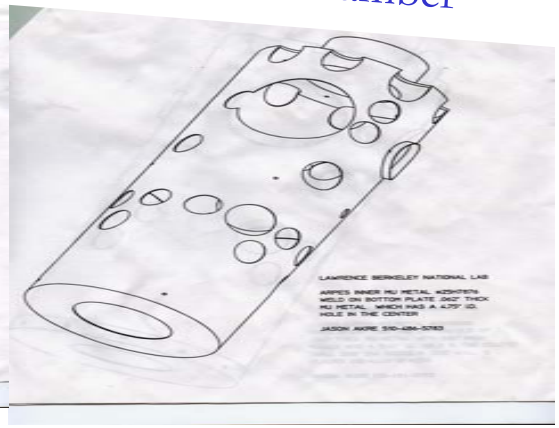




Engineering expertise is essential for making our analyzers to work

Magnetic screens /μ-metal/ go inside the chamber





Charge Density Waves

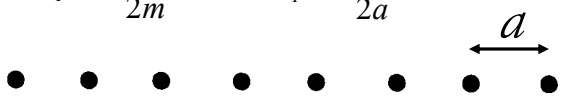
R.E. Peirls, Quantum Theory of Solids (Clarendon, Oxford, 1955); **H. Fröhlich**, Proc. R. Soc. Lond. A 223, 296 (1954); **A.W. Overhauser**, Phys. Rev. 167, 691 (1968); **S.-K. Chan** and **V. Heine**, J. Phys. F 3, 795 (1973)

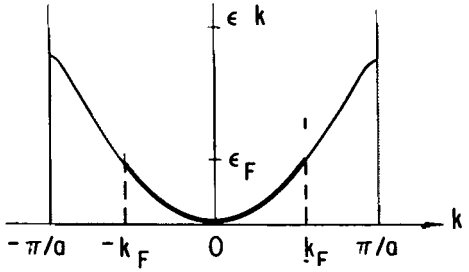
★ **G. Grüner, Density Waves in Solids (Addison-Wesley, Reading, 1994)** ★

1. Lets take one-dimensional electron gas...

$$\varepsilon(k) = \eta^2 k^2 / 2m$$

$$\varepsilon_F = \frac{\eta^2 k_F^{\ 2}}{2m} \qquad k_F = \frac{N_0 \pi}{2a}$$





2. Consider response of an electron gas to a time independent potential:

$$\phi(\vec{r}) = \int_q \phi(\vec{q}) e^{i\vec{q}\vec{r}} d\vec{q}$$

3. Rearrangement of the charge density:

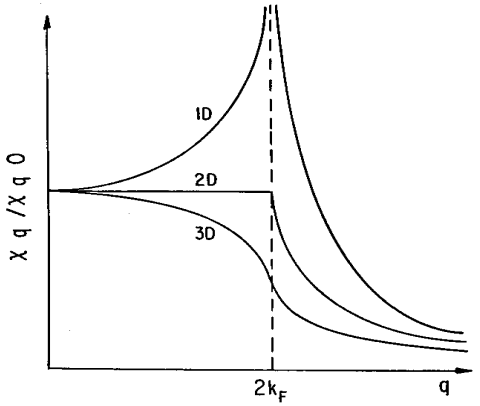
$$\rho^{ind}(\vec{q}) = \chi(\vec{q})\phi(\vec{q})$$

4. $\chi(q)$–Lindhard response function:

$$\chi(\vec{q}) = \int \frac{d\vec{k}}{(2\pi)^d} \frac{f_k - f_{k+q}}{\varepsilon_k - \varepsilon_{k+q}}$$

In one dimension:

$$\chi(q) = \frac{-e^2}{\pi \eta v_F} \ln \left| \frac{q + 2k_F}{q - 2k_F} \right|$$



$\chi(q)$ diverges at $q=2k_F$

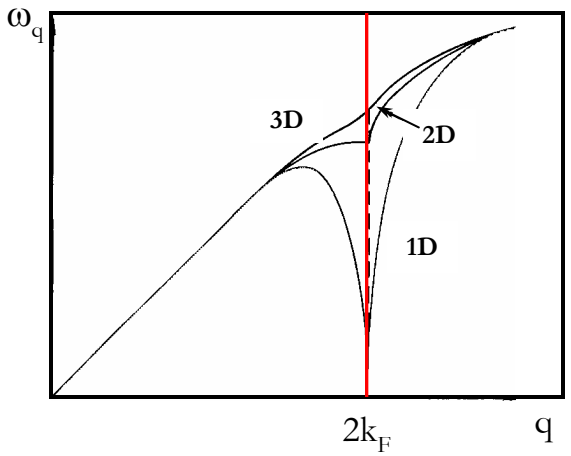
⇓

One-dimensional gas is unstable with respect to the formation of a periodically varying electron charge density

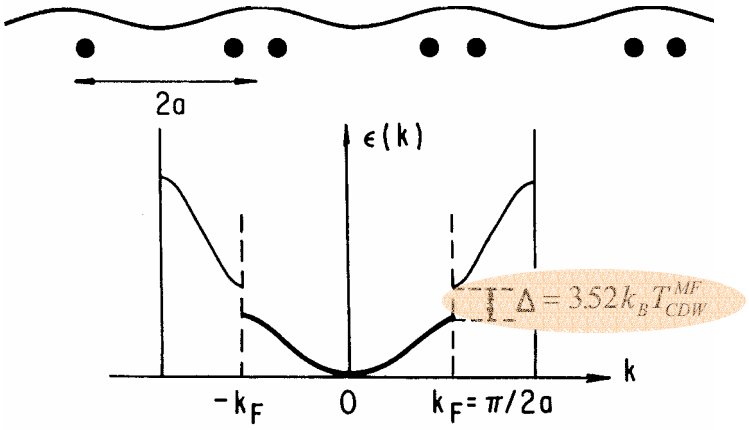
Consequences of charge modulation

/and electron-phonon coupling/

Modification of phonon spectrum
/Kohn anomaly or phonon softening at $2k_F$/

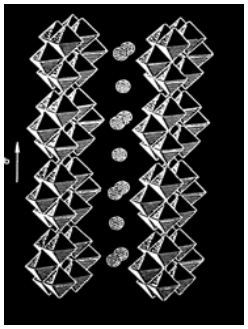


Periodic lattice modulation
and Pierls transition /opening of a gap at k_F/

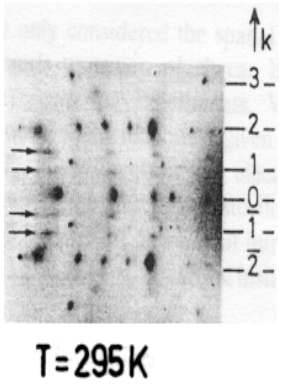


CDW in a real system: $K_{0.3}MoO_4$

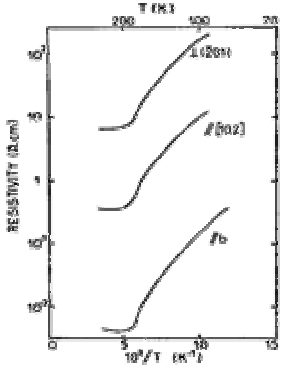
Quasi-one-dimensional
crystal structure



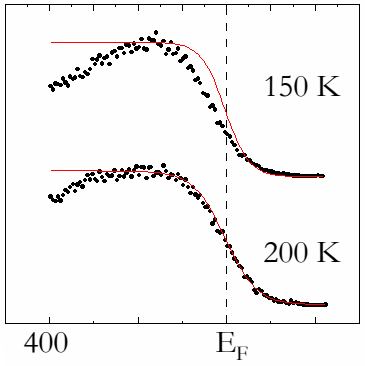
X-ray scattering



Resistivity

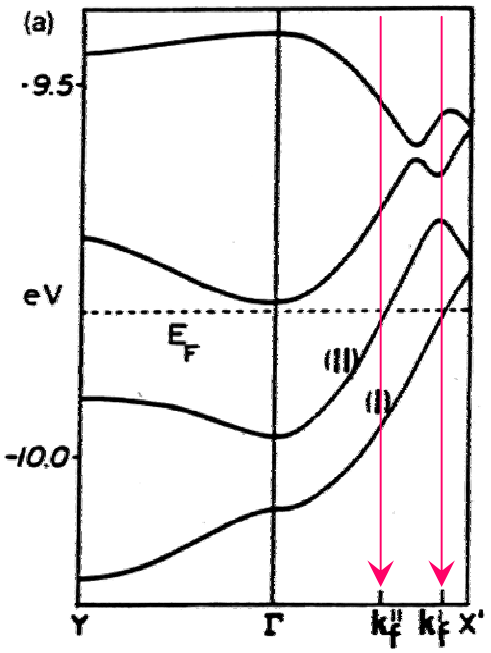


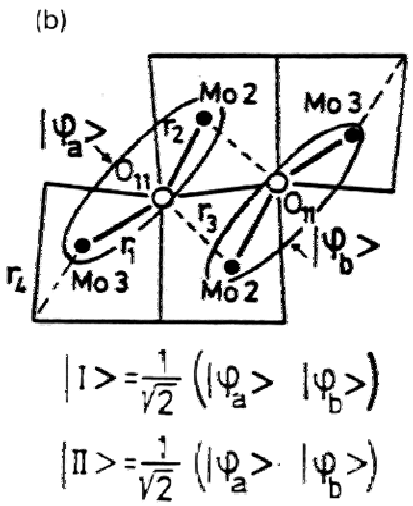
ARPES spectra at k_F



Electronic structure of $K_{0.3}MoO_3$
/tight-binding calculations/

M.-H. Whangbo and L.F. Schneemeyer, Inor. Chem. 25,2424 (1986)





$$|I> = \frac{1}{\sqrt{2}}\left(|\varphi_a> \; |\varphi_b>\right)$$

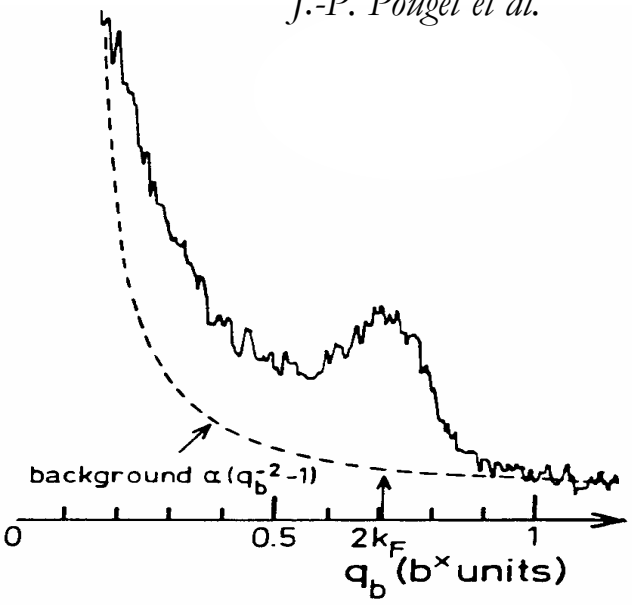
$$|II> = \frac{1}{\sqrt{2}}\left(|\varphi_a> \; |\varphi_b>\right)$$

Structural studies of $K_{0.3}MoO_3$

/incommensurate to commensurate transition/

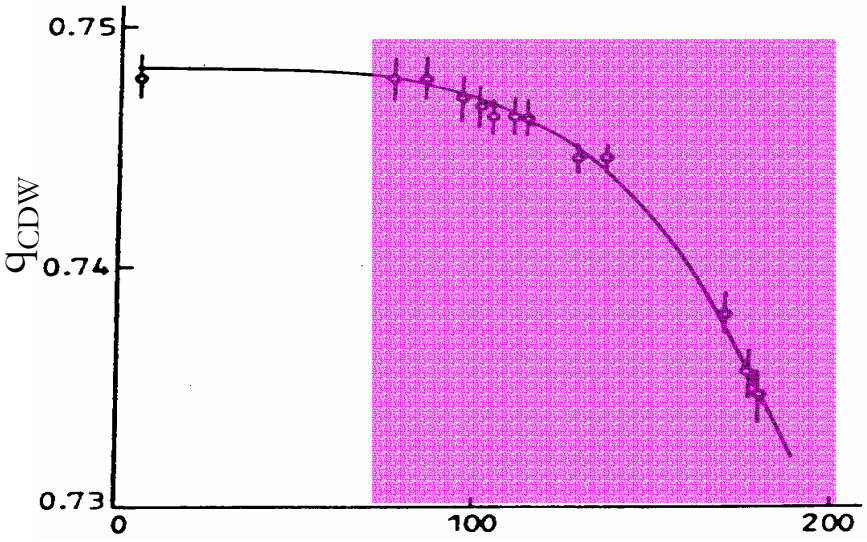
Diffuse X-ray scattering

J.-P. Pouget et al.



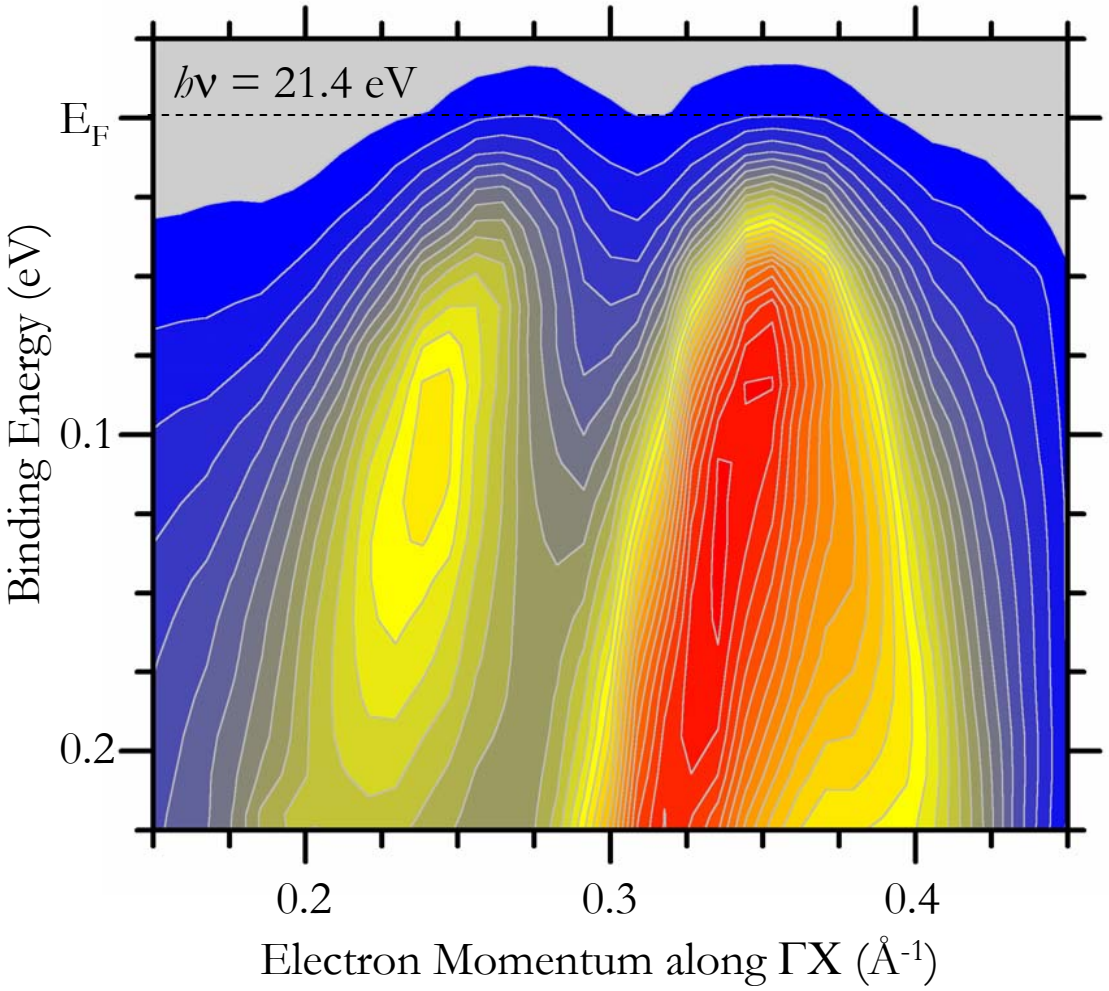
Temperature dependent neutron scattering

M.Sato, H. Fujishita and S.Hoshito,
J. Phys. C: Solid State phys., 16, L877 (1983)



Direct monitoring electron bands in $K_{0.3}MoO_3$

/3-D maps of photocurrent/



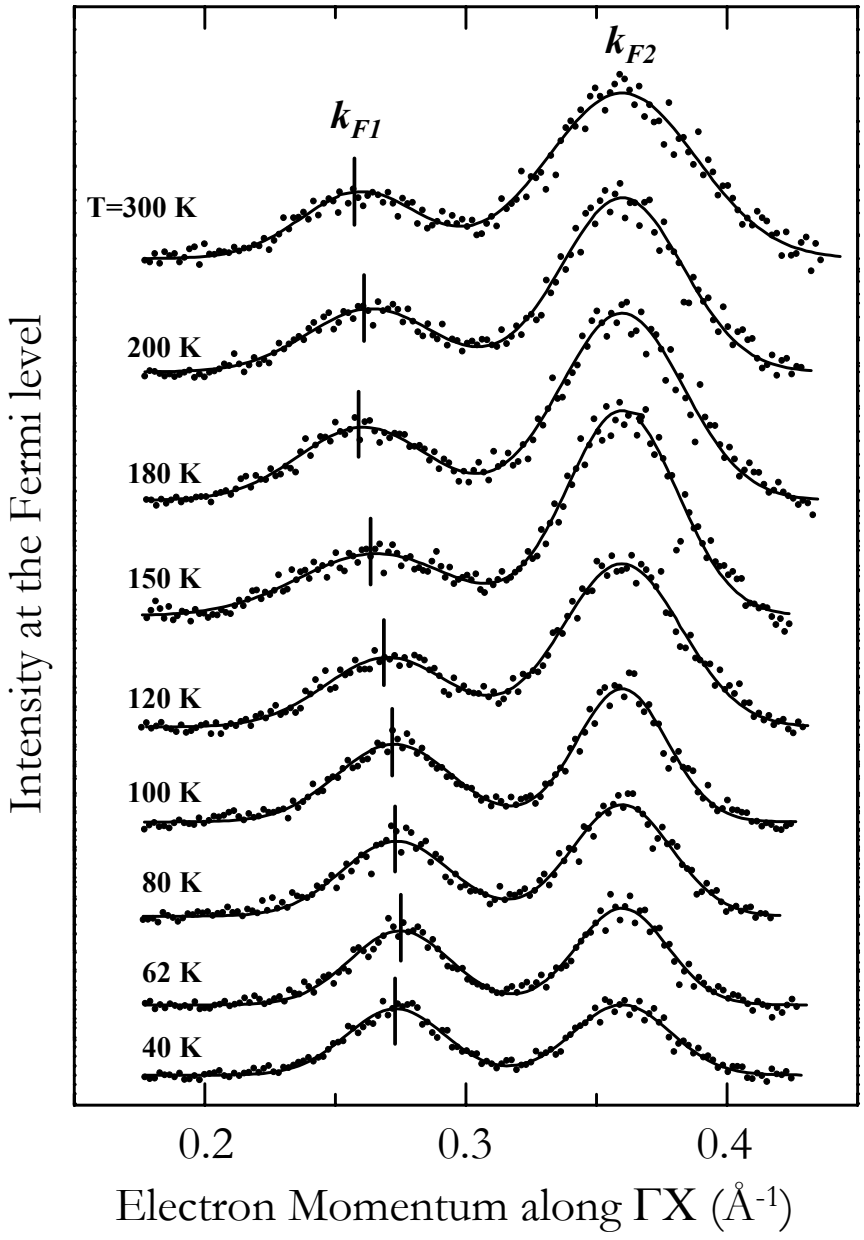
<u>Experimental details:</u>

Samples cleaved *in situ*

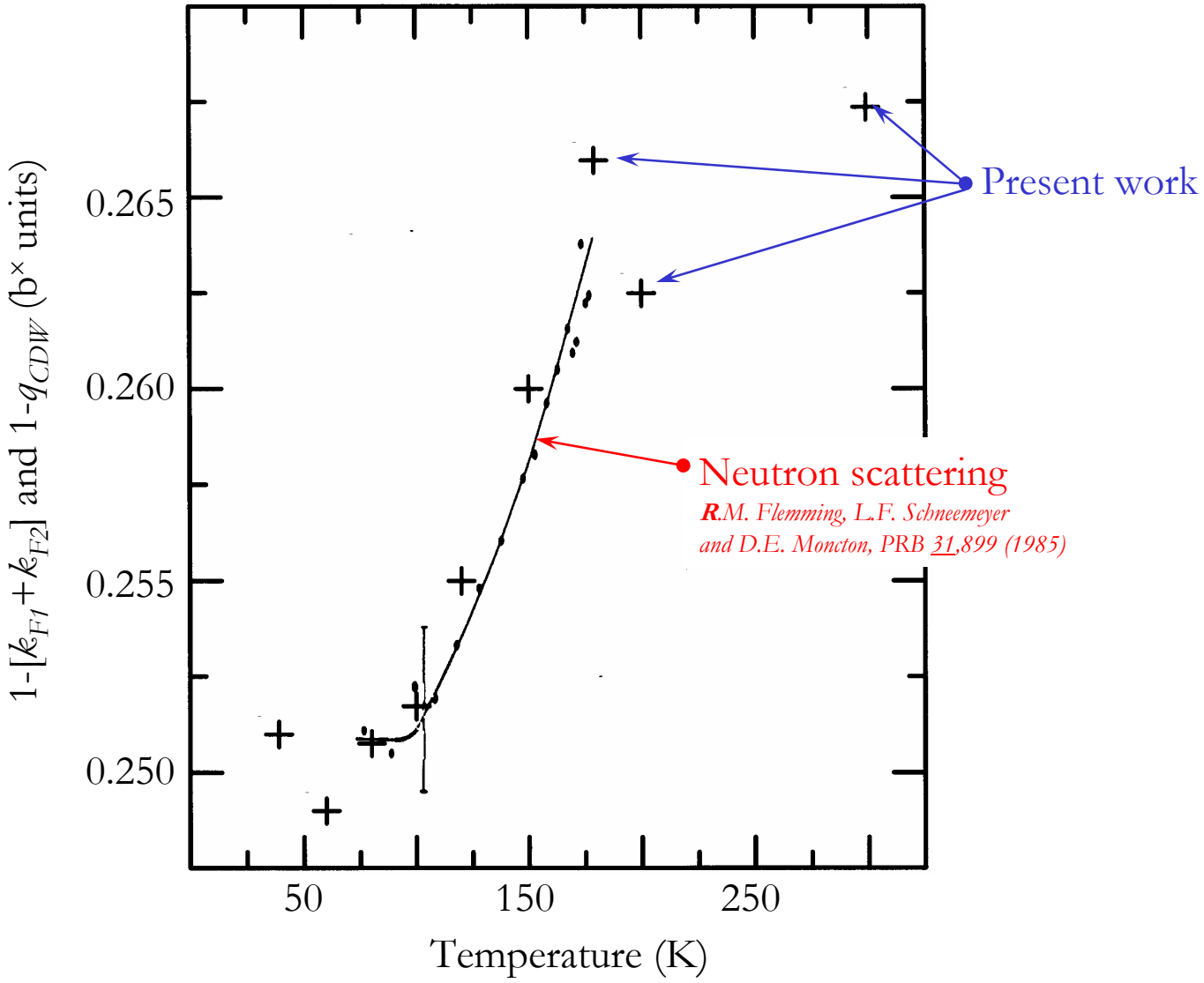
Liquid He cryostat provides temperatures from ~20 K to ~450 K

Temperature monitored with OMEGA CY7 sensor

Momentum Distribution Curves at E_F

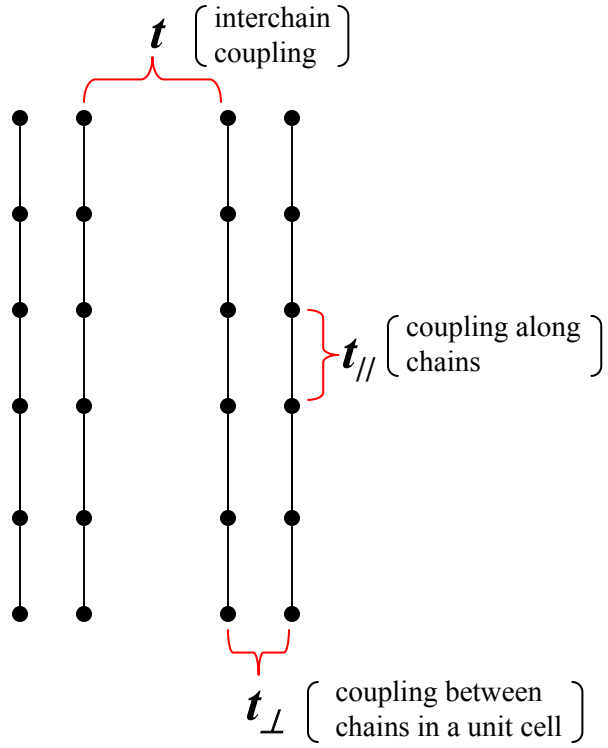


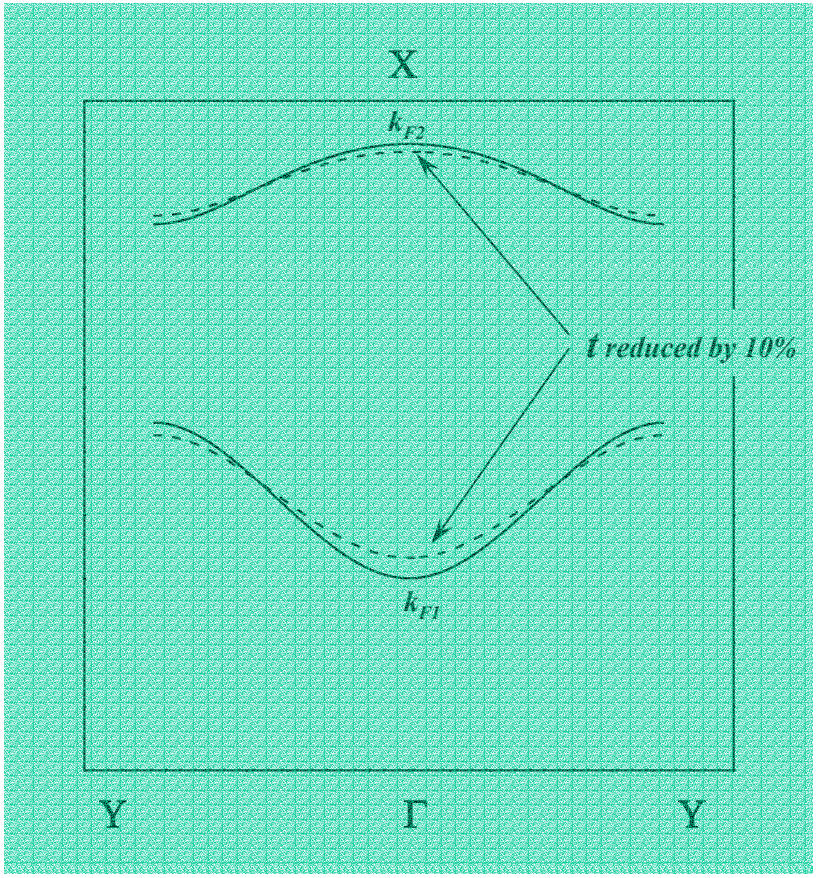
Incommensurate to commensurate CDW transition in $K_{0.3}MoO_3$ /viewed by photoemission/



Fermi surface of an array of coupled chains

/tight binding calculation/



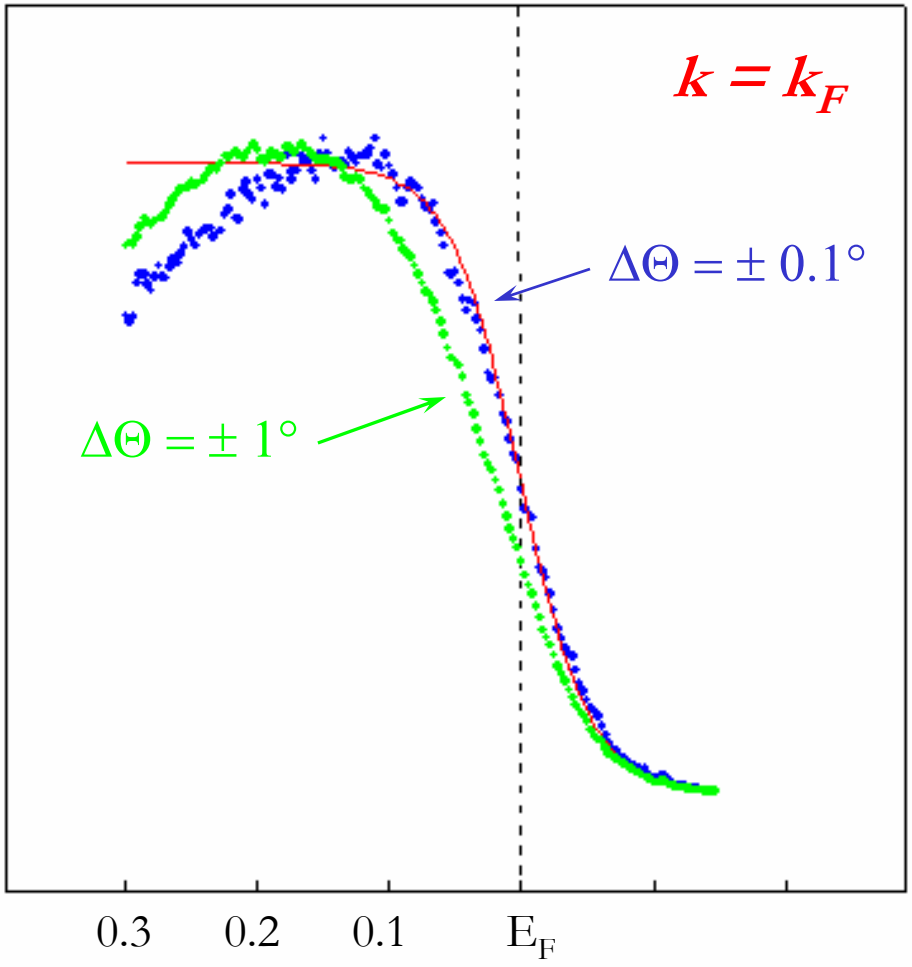


Fermi surface is given by:

$$\mu = -2cos(k_{//}) \pm (t_{\perp} + 2t_{\perp}\ t\ cos(k_{\perp}) + t)^{1/2}$$

A.V. Fedorov et al., Journal of Physics: Condensed Matter (Letters to the Editor) 12, L191 (2000)

Suppression of spectral weight in photoemission from low-dimensional conductors: influence of momentum resolution



Physical Review Letters

Home Page | Browse Available Volumes | Search | Subscriptions | Online Journal Help

Phys. Rev. Lett. Vol Page or Article #: Retrieve

Search Volumes 80 - Present: Results List

New Search General Search Help

Article Collection: View Collection Help (Click on ☐ here to add an article.)

You were searching for : ((photoemission) <and>(brookhaven <IN> aff))
You found 10 out of 12056 (10 returned)
Documents 1 - 10 listed on this page

	Score	Title	Author(s)	Citation
☑	79%	1 Doping and Temperature Dependence of the Mass Enhancement Observed in the Cuprate Bi[sub 2]Sr[sub 2]CaCu[sub 2]O[sub 8 + delta] PDF (251 kB) Zipped PDF Order	P D Johnson, T Valla, A V Fedorov	Phys. Rev. Lett. 87, 177007 (2001)
☑	79%	2 Many-Body Effects in Angle-Resolved Photoemission: Quasiparticle Energy and Lifetime of a Mo(110) Surface State PDF (735 kB) Zipped PDF Order	T Valla, A V Fedorov, P D Johnson	Phys. Rev. Lett. 83, 2085 (1999)
☑	79%	3 Temperature Dependent Photoemission Studies of Optimally Doped Bi[sub 2]Sr[sub 2]CaCu[sub 2]O[sub 8] PDF (125 kB) Zipped PDF Order	A V Fedorov, T Valla, P D Johnson	Phys. Rev. Lett. 82, 2179 (1999)
☐	77%	4 Evidence of Electron Fractionalization from Photoemission Spectra in the High Temperature Superconductors PDF (134 kB) Zipped PDF Order	D Orgad, S A Kivelson, E W Carlson	Phys. Rev. Lett. 86, 4362 (2001)
☑	77%	5 Charge-Density-Wave-Induced Modifications to the Quasiparticle Self-Energy in 2H-TaSe[sub 2] PDF (187 kB) Zipped PDF Order	T Valla, A V Fedorov, P D Johnson	Phys. Rev. Lett. 85, 4759 (2000)
☑	77%	6 Reply: Smith et al. PDF (36 kB) Zipped PDF Order	Kevin E Smith, Jinyu Xue, L-C Duda	Phys. Rev. Lett. 85, 3986 (2000)
☑	77%	7 Temperature Dependent Scattering Rates at the Fermi Surface of Optimally Doped Bi[sub 2]Sr[sub 2]CaCu[sub 2]O[sub 8 + delta] PDF (224 kB) Zipped PDF Order	T Valla, A V Fedorov, P D Johnson	Phys. Rev. Lett. 85, 828 (2000)
☑	77%	8 Electronic Structure near the Fermi Surface in the Quasi-One-Dimensional Conductor Li[sub 0.9]Mo[sub 6]O[sub 17] PDF (561 kB) Zipped PDF Order	Jinyu Xue, L-C Duda, Kevin E Smith	Phys. Rev. Lett. 83, 1235 (1999)
☐	77%	9 Magnetic Properties at Surface Boundary of a Half-Metallic Ferromagnet La[sub 0.7]Sr[sub 0.3]MnO[sub 3] PDF (211 kB) Zipped PDF Order	JH Park, E Vescovo, HJ Kim	Phys. Rev. Lett. 81, 1953 (1998)

Physical Review Letters

Home Page | Browse Available Volumes | Search | Subscriptions | Online Journal Help

Phys. Rev. Lett. Vol Page or Article #: Retrieve

Search Volumes 80 - Present: Results List

New Search General Search Help

Article Collection: View Collection Help (Click on ☐ here to add an article.)

You were searching for : ((photoemission) <and>(shen <IN> author))
You found 12 out of 12056 (12 returned)
Documents 1 - 12 listed on this page

	Score	Title	Author(s)	Citation
☑	79%	1 Anomalous Electronic Structure and Pseudogap Effects in Nd[sub 1.85]Ce[sub 0.15]CuO[sub 4] PDF (361 kB) Zipped PDF Order	N P Armitage, D H Lu, C Kim	Phys. Rev. Lett. 87, 147003 (2001)
☑	79%	2 Bilayer Splitting in the Electronic Structure of Heavily Overdoped Bi[sub 2]Sr[sub 2]CaCu[sub 2]O[sub 8 + delta] PDF (457 kB) Zipped PDF Order	D L Feng, N P Armitage, D H Lu	Phys. Rev. Lett. 86, 5550 (2001)
☑	79%	3 Superconducting Gap and Strong In-Plane Anisotropy in Untwinned YBa[sub 2]Cu[sub 3]O[sub 7 - delta] PDF (1886 kB) Zipped PDF Order	D H Lu, D L Feng, N P Armitage	Phys. Rev. Lett. 86, 4370 (2001)
☑	79%	4 Superconducting Gap Anisotropy in Nd[sub 1.85]Ce[sub 0.15]CuO[sub 4]: Results from Photoemission PDF (188 kB) Zipped PDF Order	N P Armitage, D H Lu, D L Feng	Phys. Rev. Lett. 86, 1126 (2001)
☑	79%	5 Fermi Surface, Surface States, and Surface Reconstruction in Sr[sub 2]RuO[sub 4] PDF (257 kB) Zipped PDF Order	A Damascelli, D H Lu, K M Shen	Phys. Rev. Lett. 85, 5194 (2000)
☑	77%	6 Dual Nature of the Electronic Structure of (La[sub 2 - x - y]Nd[sub y]Sr[sub x])CuO[sub 4] and La[sub 1.85]Sr[sub 0.15]CuO[sub 4] PDF (204 kB) Zipped PDF Order	X J Zhou, T Yoshida, S A Kellar	Phys. Rev. Lett. 86, 5578 (2001)
☐	77%	7 Evidence of Electron Fractionalization from Photoemission Spectra in the High Temperature Superconductors PDF (134 kB) Zipped PDF Order	D Orgad, S A Kivelson, E W Carlson	Phys. Rev. Lett. 86, 4362 (2001)
☑	77%	8 Angle-Resolved Photoemission Study of Insulating and Metallic Cu-O Chains in PrBa[sub 2]Cu[sub 3]O[sub 7] and PrBa[sub 2]Cu[sub 4]O[sub 8] PDF (163 kB) Zipped PDF Order	T Mizokawa, C Kim, Z-X Shen	Phys. Rev. Lett. 85, 4779 (2000)
☑	77%	9 Evidence for an Energy Scale for Quasiparticle Dispersion in Bi[sub 2]Sr[sub 2]CaCu[sub 2]O[sub 8] PDF (175 kB) Zipped PDF Order	P V Bogdanov, A Lanzara, S A Kellar	Phys. Rev. Lett. 85, 2581 (2000)